Embankment Slope Stability

Best Practices in Dam and Levee Safety Risk Analysis

Part D - Embankments and Foundations

Chapter D-5

Last modified June 2017, presented July 2018

US Army Corps of Engineers®

Objective of Chapter

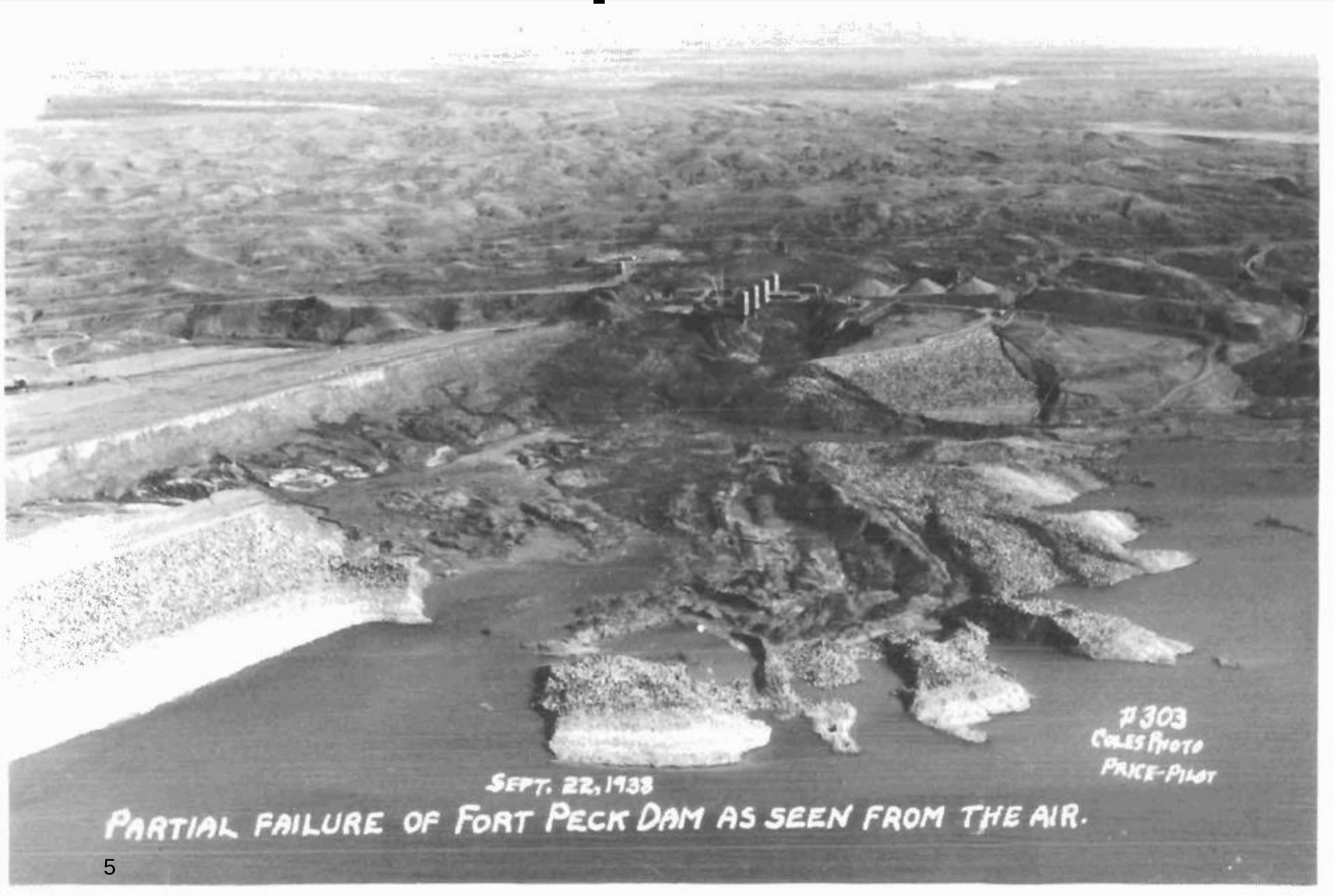
- Understand slope stability issues that may affect a dam’s or levee’s risk of breach.
- Provide guidance on consideration and selection of soil strengths, pore pressures and loading conditions for slope stability analysis for risk assessments.

Key Concepts

- Formational processes, stress history and current state of stress will affect whether it is “dense” or “loose”
- “Dense/overconsolidated” soils dilate and “loose/normally consolidated” soils contract during shear
- Drainage condition (i.e., drained or undrained loading) is a function of the permeability of the soil and the rate of consolidation and shear loading
- Negative (dense) or positive (loose) shear-induced pore pressures can develop dependent on drainage condition and can increase or decrease the soil’s strength
- Soil strength changes with time

- USACE slope instability issues
  - “during construction and end of construction” conditions
  - A few dams have had issues on “sunny days” or during sudden drawdown conditions.
  - Levees have had more serious issues that have occurred from during construction to flood loading conditions
    - New Orleans
- Reclamation has had few instability issues
  - Belle Fouche Dam, SD and Meeks Cabin Dam, WY
  - San Luis Dam, CA

Ft Peck Dam Upstream Slide 1938



View Looking East Towards the Right Abutment, Note Slide Area.

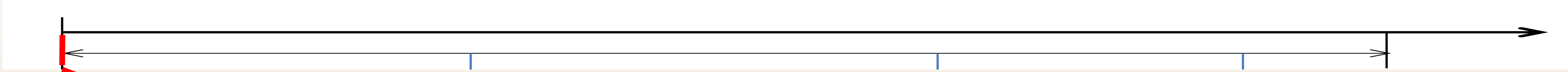
Key information for doing proper embankment slope instability analysis

- Geometry and geology
- Shear strength
- Stresses (total stresses and pore pressures)
- Pore pressures from hydrostatic, seepage conditions and shear induced

Slope Instability Triggers

- Rainfall Infiltration (from cracks or poor drainage at crest)
- Removal of toe support (from erosion or excavation)
- Surcharge loading at crest or foundation
- Rapid drawdown
- Changes in seepage or groundwater (e.g. irrigation on abutment)
- Other conditions that change vertical or horizontal stresses (e.g. water line)

TIME



End of Construction

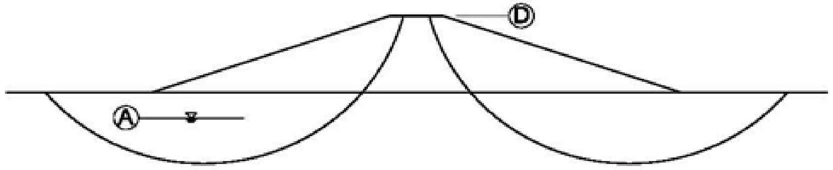
End of Primary Consolidation

CASE I

END OF CONSTRUCTION

T = 0 years

(minimum NC undrained strength)



SLOPE: WATERSIDE & LANDSIDE
LEVEE EL: D
WATER LOAD: A

SHEAR STRENGTH	PORE-WATER
LOW PERMEABLE: UU	N/A
FREE DRAINING: CD	A

FACTOR OF SAFETY: 1.3 MINIMUM

TIME

End of Construction

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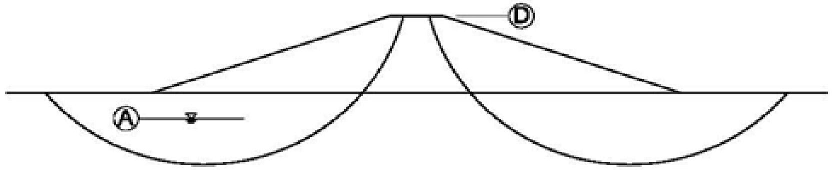


SLOPE: WATERSIDE & LANDSIDE
LEVEE EL: D
WATER LOAD: A

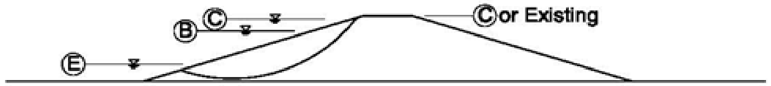
SHEAR STRENGTH	PORE-WATER
LOW PERMEABLE: UU	N/A
FREE DRAINING: CD	A

FACTOR OF SAFETY: 1.3 MINIMUM

CASE II

SUDDEN DRAWDOWN

T = 0 years to end of Primary Consolidation



SLOPE: WATERSIDE
LEVEE EL: C or Existing
WATER LOAD: C to E
B to E

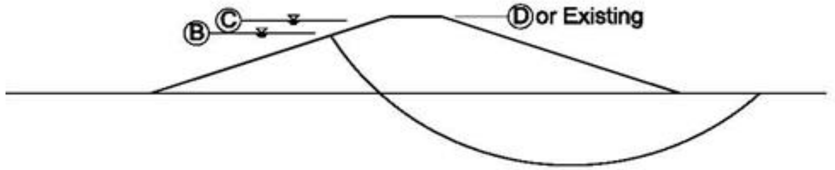
SHEAR STRENGTH	PORE-WATER
LOW PERMEABLE: 3-STAGE	C or B Stage 1
FREE DRAINING: CD	C or B All Stages

FACTOR OF SAFETY: 1.2 MINIMUM LOADING B to E (Long Duration)
1.0 MINIMUM LOADING B to C (Short Duration)
1.0 MINIMUM LOADING C to E (Long or Short Duration)

TIME

End of Construction

End of Primary Consolidation



CASE III

FLOOD LOADING

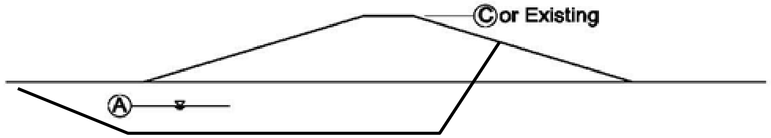
T = 0 years to end of Primary Consolidation

SLOPE: LANDSIDE
LEVEE EL: D or Existing
WATER LOAD: B & C

SHEAR STRENGTH	PORE-WATER
LOW PERMEABLE: UU (1,2)	N/A
LOW PERMEABLE: CD (3)	B or C
FREE DRAINING: CD	B or C

FACTOR OF SAFETY: 1.4 MINIMUM LOADING B
1.3 MINIMUM LOADING C

NOTES:
(1) T = 0 (New Levee): Undrained shear strengths based on pre-construction in situ conditions.
(2) T > 0 yrs and OCR < say 2 - 4: Undrained shear strengths based in existing in situ conditions at time of evaluation.
(3) OCR > say 2 to 4: Drained shear strengths.



CASE IV

SEISMIC

T = 0 years to end of Primary Consolidation

SEE ER 1110-2-1806 FOR GUIDANCE. GUIDANCE FOR SEISMIC STABILITY ANALYSIS OF LEVEES IS UNDER PREPARATION (ETL 1110-2-XXXX).

Analysis Condition	Shear Strength[a]	Pore Water Pressure
Case I. During Construction and End-of-Construction	Free draining soils - use drained strengths	Free draining soils - Pore water pressures can be estimated using analytical techniques such as hydrostatic pressure computations for no flow or steady seepage analysis techniques (flow nets, finite element/difference analyses).
	Low permeability soils wet of critical – use undrained strengths based on pre-construction effective stress conditions for soils with OCR < 2 to 4	Low permeability soils wet of critical – use total stresses with pore water pressures set to zero in the slope stability computations for materials with OCR < 2 to 4
	Low permeability soils dry of critical – use drained strengths when OCR > 2 to 4.[b]	Low permeability soils dry of critical – use effective stresses with appropriate construction pore pressures, often assumed to be hydrostatic OCR > 2 to 4
Case II. Sudden Drawdown Conditions	Free draining soils - use drained strengths	Free draining soils - First stage computations (before drawdown) - steady state seepage pore pressures as described for steady state seepage condition. Second and third stage computations (after drawdown) - pore water pressures estimated using same techniques as for steady seepage, except with lowered water levels.
	Low permeability soils - Three stage computations: First stage use effective stresses; second stage use undrained shear strengths and total stresses; third stage use drained strengths (effective stresses) or undrained strengths (total stresses) depending on which strength is lower - this will vary along the assumed shear surface.	Low permeability soils - First stage computations – steady state seepage pore pressures as described for steady state seepage condition. Second stage computations - Total stresses are used, pore water pressures are set to zero. Third stage computations - Use same pore pressures as free draining soils if drained strengths are being used; where undrained total stress strengths are used, pore water pressures have no effect and can be set to zero.

Analysis Condition	Shear Strength[a]	Pore Water Pressure
Case III. Flood Loading	Free draining soils - use drained strengths. Residual strengths should be used where previous shear deformation or sliding has occurred.	Free draining soils - Pore water pressures can be estimated using analytical techniques such as hydrostatic pressure computations for no flow or steady seepage analysis techniques (flow nets, finite element/difference analyses).
	Low permeability soils wet of critical – use undrained strengths based on pre-flood effective stress conditions for soils with OCR < 2 to 4	Low permeability soils wet of critical – use total stresses with pore water pressures set to zero in the slope stability computations for materials with OCR < say 2 to 4.
	Low permeability soils dry of critical – use drained strengths using steady state seepage pore pressures.[b]	Low permeability soils dry of critical – use effective stresses under steady state seepage flood loading for materials with OCR > say 2 to 4.
Case IV. Seismic	(see ETL 1110-2-XXX, Guidelines for Seismic Evaluation of Levees	

[a] Effective stress parameters can be obtained from consolidated-drained (CD) tests (either direct shear or triaxial) or consolidated-undrained (CU) triaxial tests on saturated specimens with pore water pressure measurements. Direct shear or Bromhead ring shear tests should be used to measure residual strengths. Undrained strengths can be obtained from unconsolidated-undrained (UU) and direct simple shear tests. Undrained shear strengths can also be estimated using consolidated-undrained (CU) tests on specimens consolidated to appropriate stress conditions representative of field conditions, but these strengths may be unconservative. The CU or "total stress" envelope, with associated c and φ parameters, should not be used. OCR is estimated based on the maximum past pressure and the effective stress prior to the flood load.
[b] For saturated soils with OCR < 2 to 4, use $\varphi = 0$.

aka "Rapid Flood Loading" of Soft Materials

New Orleans Parish

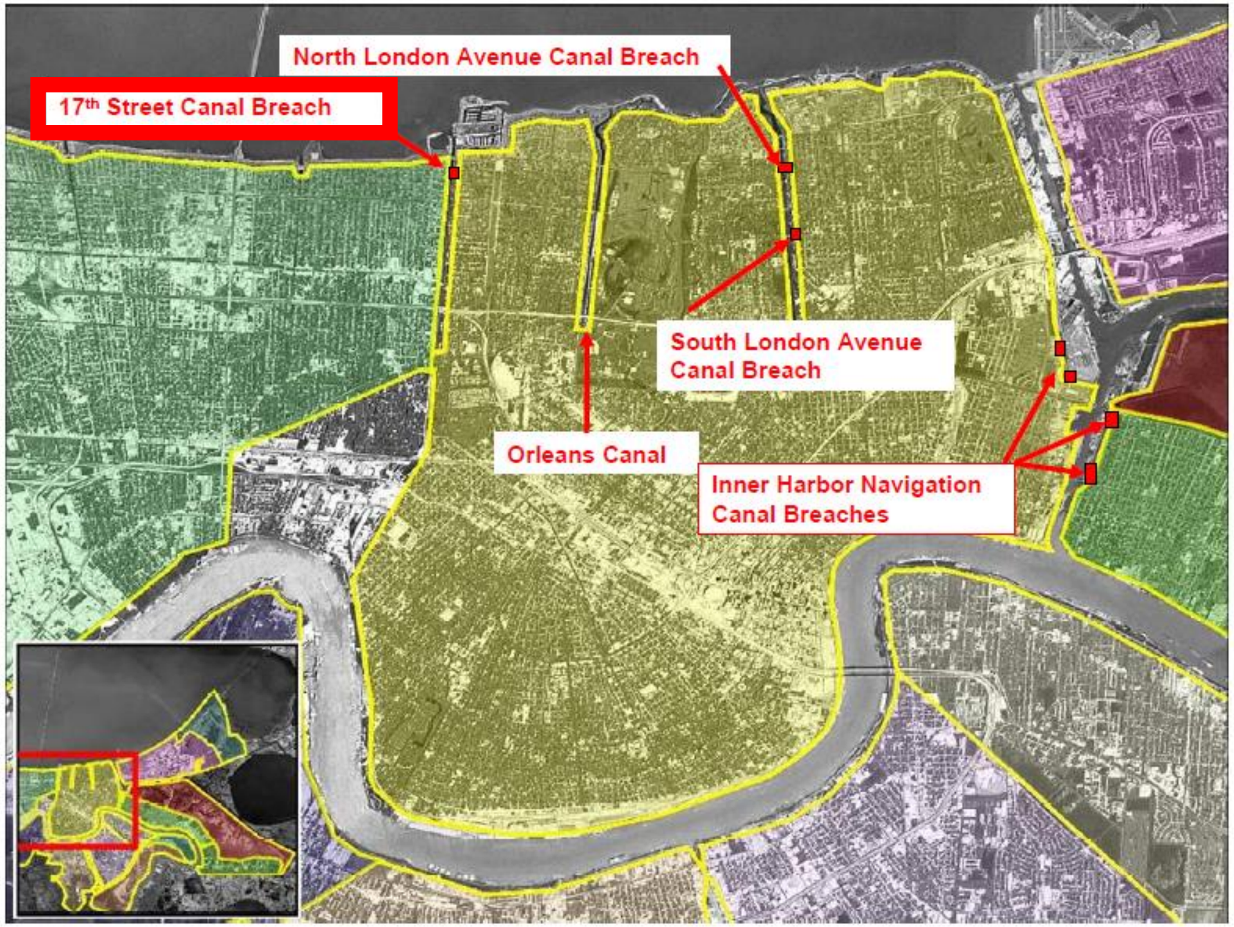
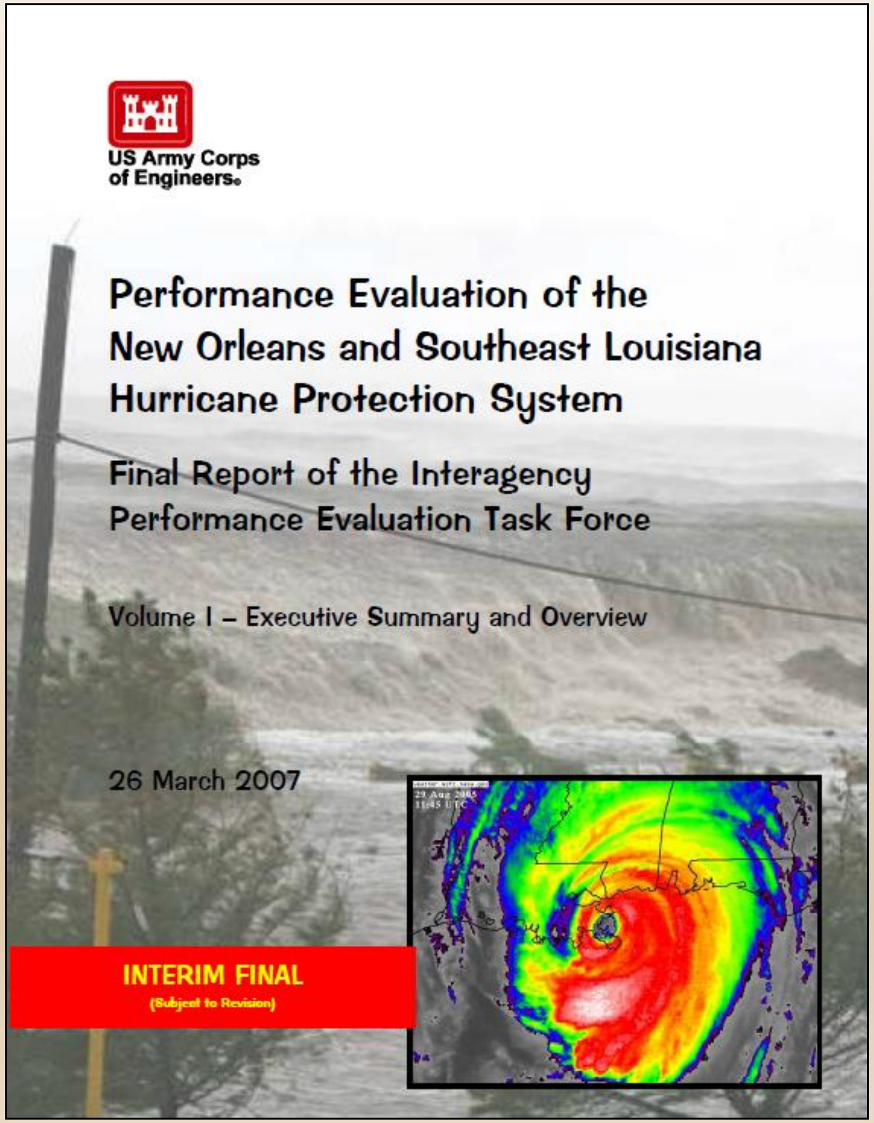


Figure 1-1. Location of Orleans Parish canals

Photos from Brett Duke, Online Times-Picayune archive

Examples – "Soft" Wet-of-Critical

Shear Induced Positive Pore Pressures – Use Undrained Strengths



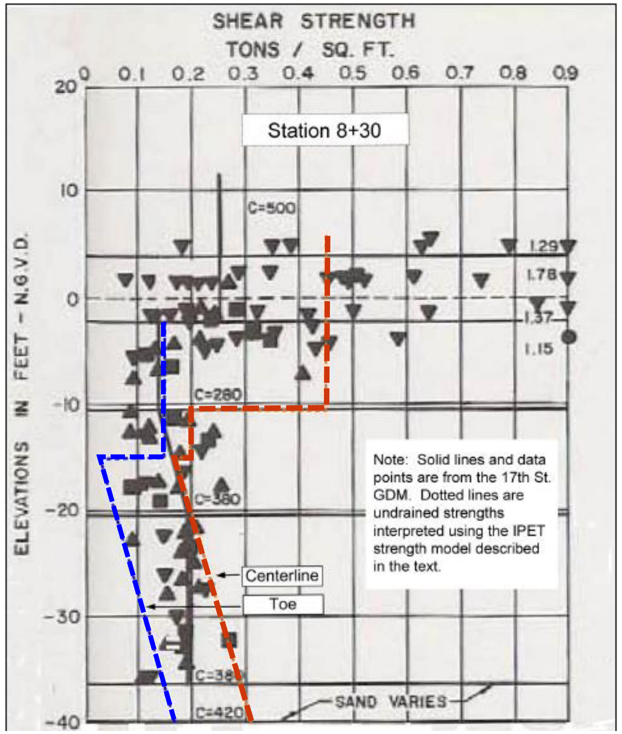
Appendix 1
Soil Data Report for 17th Street Canal

Introduction

This is a data report detailing the data collected by the Interagency Performance Evaluation Task Force (IPET) to support the analysis of the I-wall section that breached at the 17th Street Canal as a result of Hurricane Katrina on August 29, 2005. The location of the 17th Street Canal is shown in Figure 1-1. The site of the breach, located on the east bank near the north end of the canal, is also noted on Figure 1-1.

The data will be used in the Floodwall and Levee Performance Analysis task as part of its effort to determine how the flood protection structures performed in the face of the forces to which they were subjected by Hurricane Katrina, and to compare this performance with the design intent, the actual as-built condition, and observed performance. This effort includes understanding why certain structures failed catastrophically and why others did not. The effort will determine, in detail, how the levees and floodwalls performed during Hurricane Katrina. These studies will be documented in a series of reports. The series of reports will start with data reports detailing the data collected on the site conditions at 17th Street Canal, London Avenue Canal, Orleans Canal, and Inner Harbor Navigation Canal, as noted on Figure 1-1.

Design v. IPET Strengths and Stability



Undrained strength profiles for 17th St Wall Design compared to IPET Strength Model, Sta 8+30

Undrained Strengths

Phi = 0

C = f(depth)

Su/p' ~ 0.24

Note – Current USACE Slope Stability EM 1110-2-1913 (2003) Recommends Drained Strength for Steady State Seepage Analysis and Does Not Acknowledge This Undrained Loading Condition

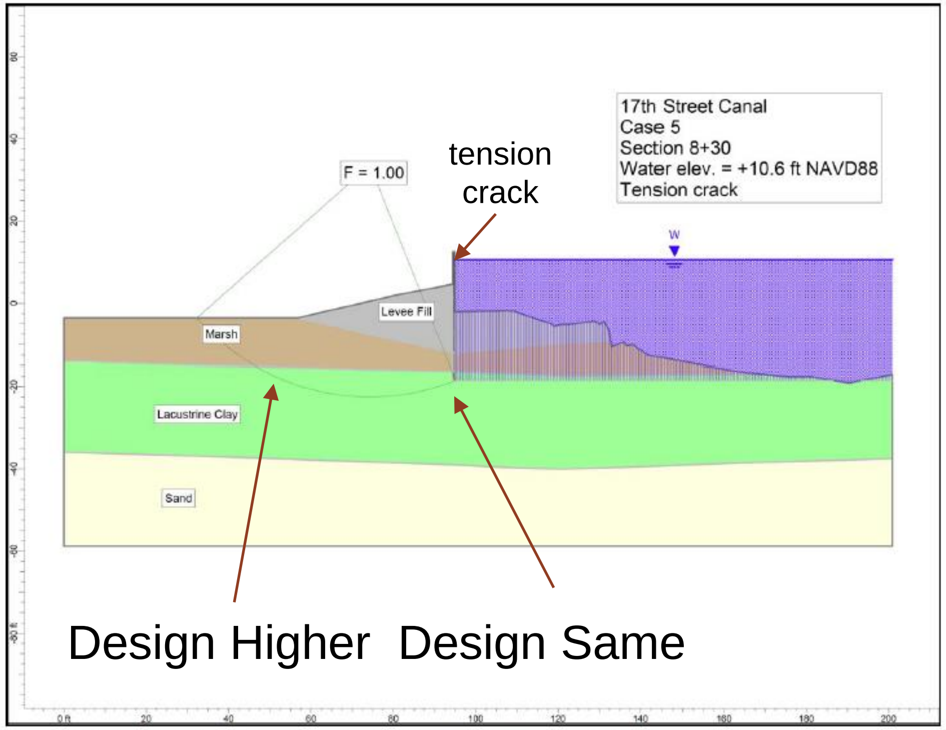


Figure 4-5. Critical Circle for 17th Street Canal Station 8+30 – Water Elevation 10.6 ft, Tension Crack.

It appears that the most important difference between the conditions used as the basis for design and the conditions defined in this report is related to the strengths of the marsh layer and clay soils beneath the slopes and beyond the toe of the levee. The design strengths and the IPET strengths are very nearly the same beneath the crest of the levee. However, beneath the levee slopes, and beyond the toe, the design strengths were higher than the IPET strengths.

Major sources of uncertainty in some cases:

- In situ large scale shear strengths versus lab testing results
- Actual pore pressures versus predicted or assumed for analysis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Embankment Instability

Contributing Factor: Slope Stability (Embankment Slides)

- Spring 2007, Storm events saturate the levees following extended dry period.
- Several levee embankment slides develop throughout the system in < 72 hours.
- Floodway monitored using Dallas PD air support and ground surveillance.
- Temporary repair efforts from the levee crest were not successful.

Embankment Instability

Contributing Factor: Encroachments (Utilities)

- 30 November 2010, Leaking 48-inch water main that crosses over the levee caused a slide of the levee embankment.
- This line was thought to be abandoned per the available USACE design & construction documents.
- Deteriorated valves could not be completely shut off to restrict flow, thus repairs were made with partial flow.
- USACE and CoD are evaluating all similar utilities to determine the appropriate mitigation solution.

Comments and Questions